

# Searches for Supersymmetry at the Tevatron

Rencontres de Moriond, QCD

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Song Ming Wang

Academia Sinica

On behalf of the CDF and DØ Collaborations

# Outline

- Brief introduction to SUSY
- SUSY searches at Tevatron
- Some selected analyses in final states :
  - Multi-lepton
  - Jets and Missing Transverse Energy
  - Photons
  - Long-lived
- Summary

# Supersymmetry

- A popular extension to the SM
  - Unifies gauge couplings (if  $M_{\text{SUSY}} < \text{few TeV}$ )
  - Incorporate gravity
  - Solve the “fine-tuning” problem (if  $M_{\text{SUSY}} < \text{few TeV}$ )
  - Provide a Dark Matter candidate
- Postulate symmetry between boson and fermion particles
  - Every SM particle has a SUSY partner with same quantum numbers except spin (differ by 1/2)

$$e, \nu, u, d, \dots (\text{spin } 1/2) \Rightarrow \tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}, \dots (\text{spin } 0)$$

$$\gamma, W^\pm, Z^0, g, \dots (\text{spin } 1) \Rightarrow \tilde{\chi}_{1,2,3,4}^0, \tilde{\chi}_{1,2}^\pm, \tilde{g} \quad (\text{spin } 1/2)$$

- New quantum number : R-parity =  $(-1)^{3B+L+2S}$ 
  - Particles:  $R=1$ ,    SParticles:  $R=-1$

# Phenomenology of SUSY

## R-parity is conserved :

- SUSY particles are pair produced
- Lightest SUSY Particle (LSP) stable
  - If neutral  $\Rightarrow$ 
    - escape detection  $\Rightarrow$  Missing Energy (MET) signature !
    - candidate for Cold Dark Matter !

- SUSY is broken ( $M_{\text{SUSY}} > M_{\text{SM}}$ )
- Some SUSY breaking models

## mSUGRA

- SUSY mediated by gravity
- LSP most likely is :  $\tilde{\chi}_1^0$
- $M_{\tilde{\chi}_1^\pm} \approx M_{\tilde{\chi}_2^0} \approx 2M_{\tilde{\chi}_1^0}$

## R-parity not conserved :

- SUSY particle can be singly produced
- LSP decays to SM particles, no dark matter candidate
- Process would violate either lepton or baryon quantum numbers

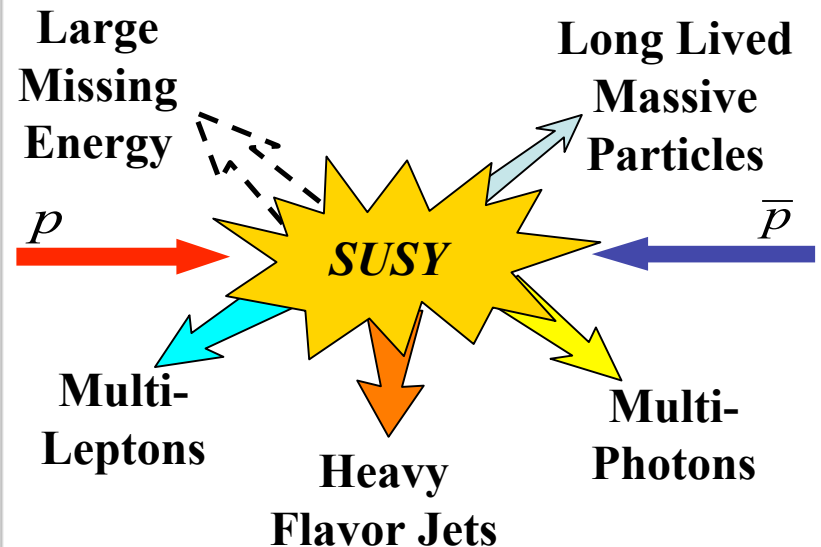
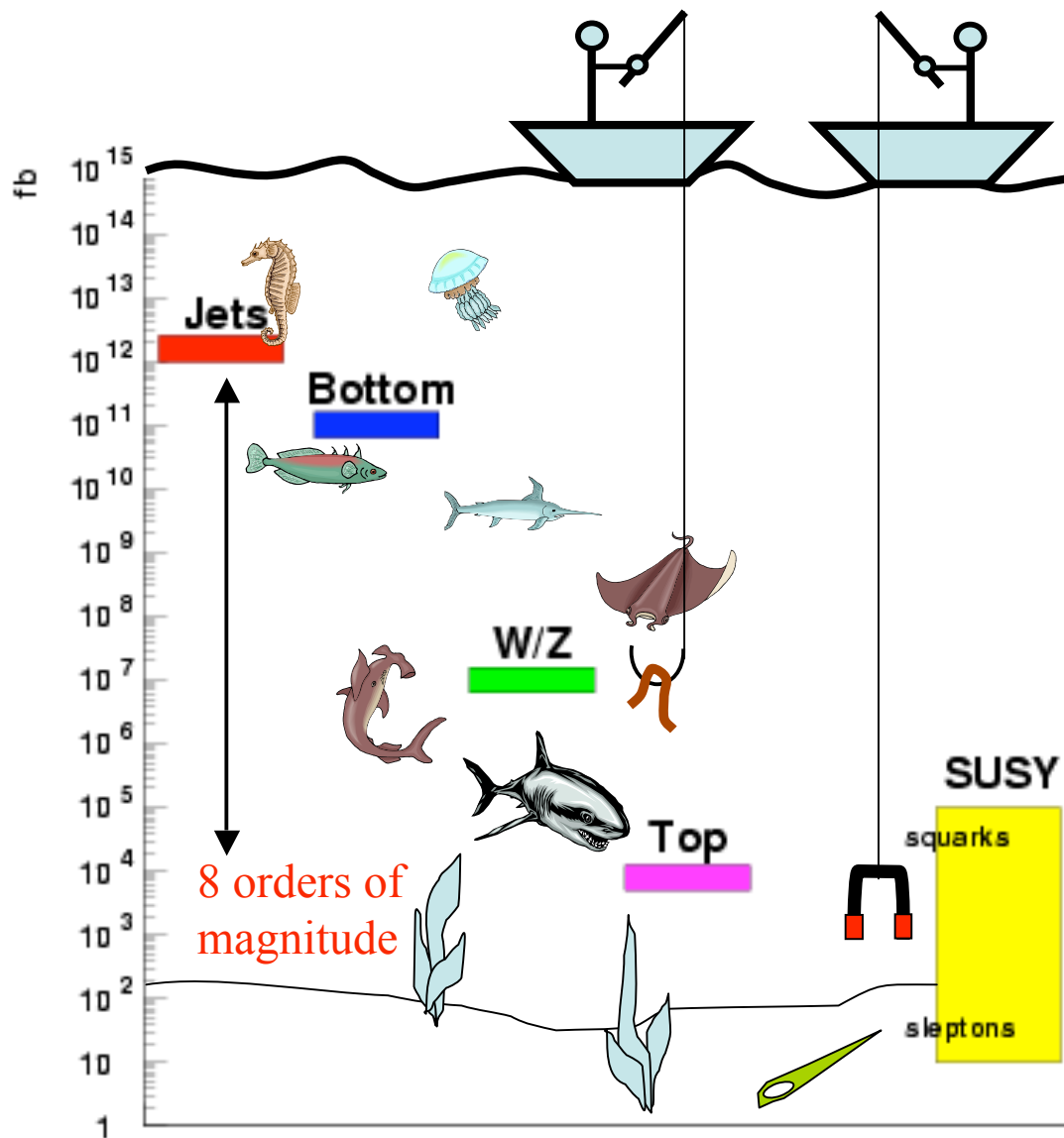
## GMSB

- SUSY mediated by gauge fields
- LSP :  $\tilde{G}$
- Phenomenology mostly determined by the NLSP (slepton or neutralino)

# SUSY at the Tevatron

- Predicted rates for SUSY are LOW !!!

• Need to look for distinctive signature to distinguish from SM background



- Present results using data samples :  $300 \text{ pb}^{-1}$  to  $1 \text{ fb}^{-1}$



# Searches for Chargino/Neutralino in MET+Leptons



- Pair production of chargino/neutralino can produce multi-lepton and MET in final state (R-parity conservation)

⇒ Very clean, “Gold Plated” signature, but :

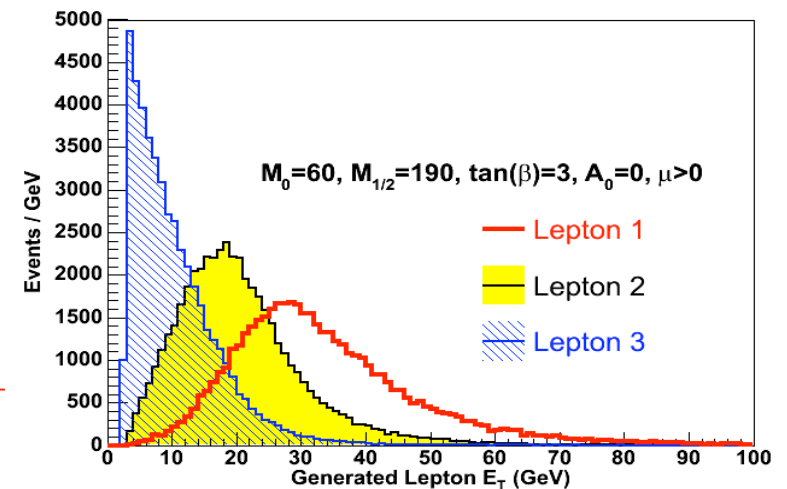
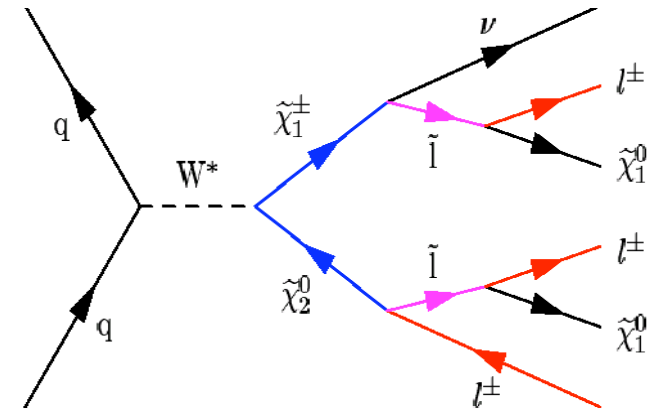
- Low cross section (x BR)
- Soft lepton

⇒ Need large integrated luminosity

⇒ Combine various final states

## General search strategy (CDF and DØ) :

- Two isolated leptons (e or  $\mu$ )
- Additional isolated lepton or track (for Tri-lepton ch.)
- Require some MET
- Veto events where  $M_{l+l-}$  in  $J/\psi$ ,  $\Upsilon$ , Z peaks



## Main Background :

- DY, Di-bosons, jets faking leptons, conversions



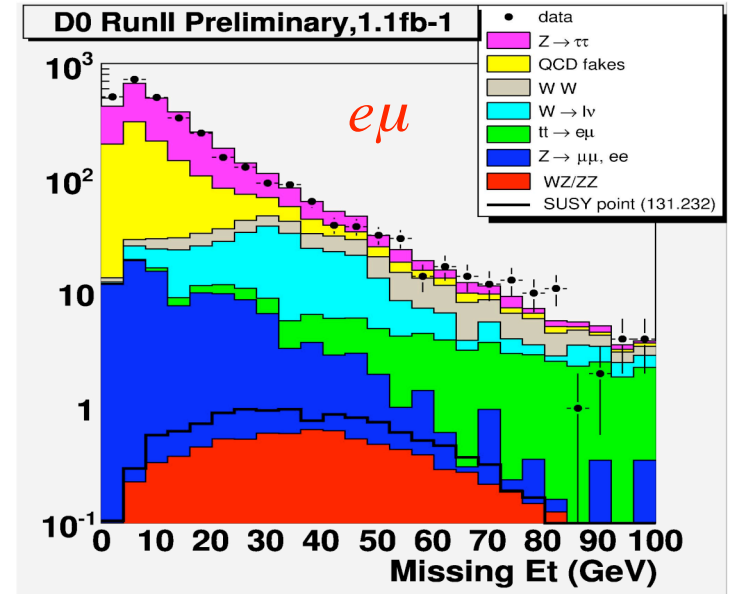
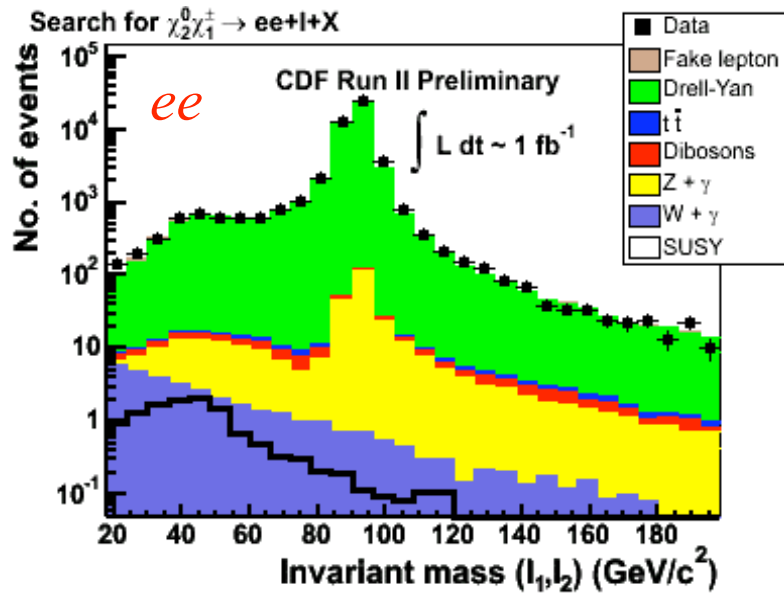
# Searches for Chargino/Neutralino in MET+Leptons



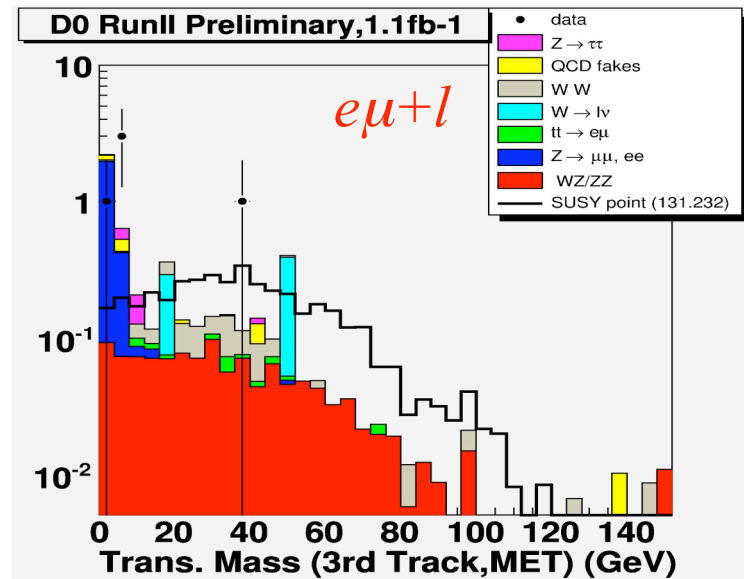
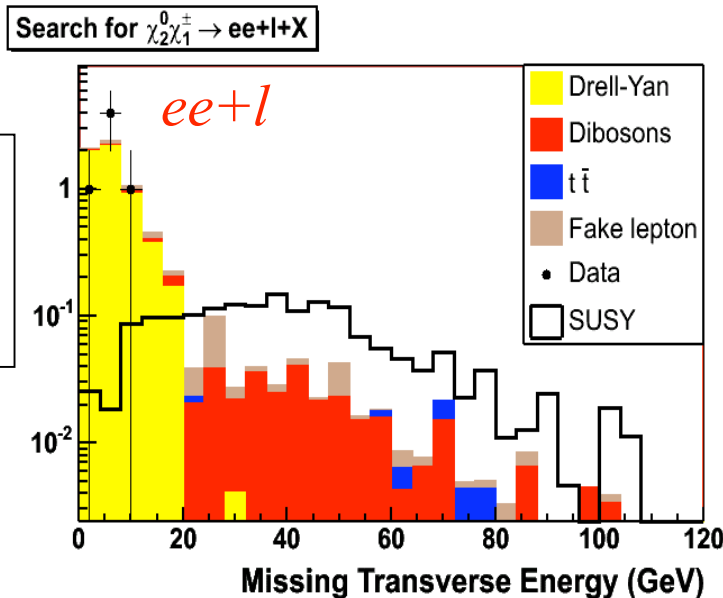
$ee+l$

$e\mu+l$

Pre-  
selection  
(req. 2  
leptons)



After  
almost all  
selections





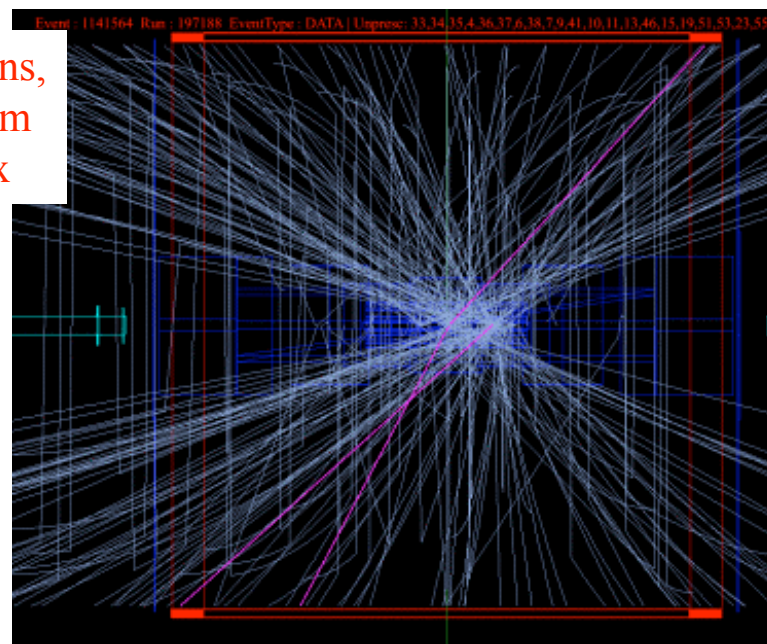
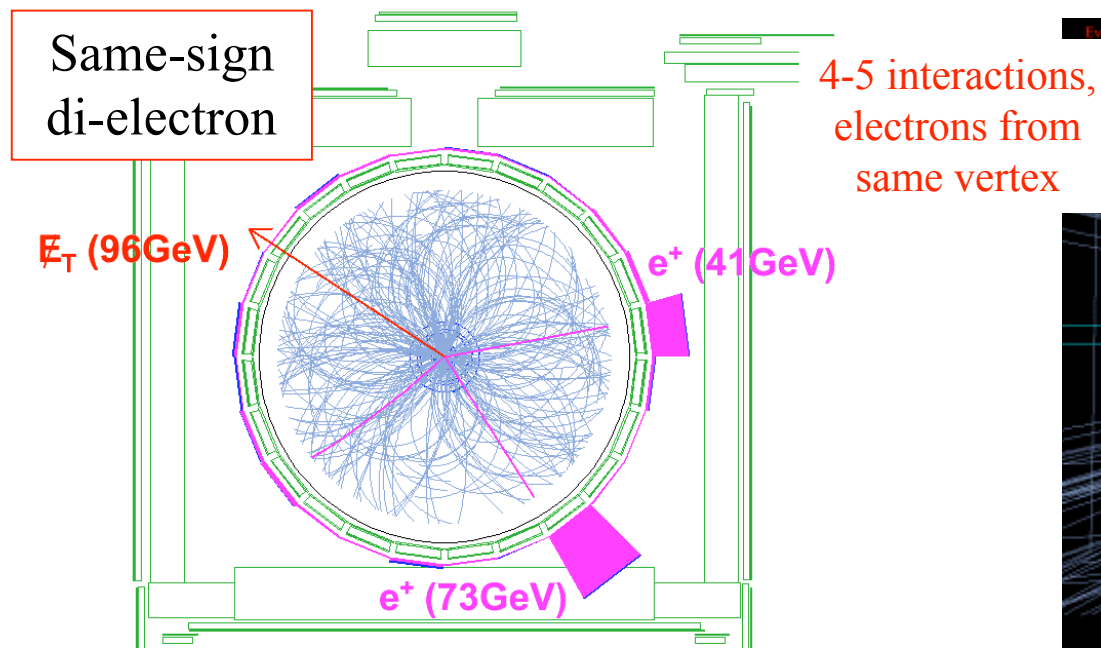
# Searches for Chargino/Neutralino in MET+Leptons



CDF	$L$ (fb <sup>-1</sup> )	#Predicted Bkg	#Obs. Data
ee+l (lowpt)	1	0.97±0.28	3
μμ+l (low pt)	1	0.40±0.12	1
ell	1	0.75±0.36	0
μll	0.75	1.26±0.27	1
$e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$	1	7.8±1.1	13

DØ	$L$ (fb <sup>-1</sup> )	#Predicted Bkg	#Obs. Data
ee+l	1.1	0.76±0.67	0
μμ+l	1.1	0.32 <sup>+0.73</sup> <sub>-0.03</sub>	2
eμ+l	1.1	0.94 <sup>+0.40</sup> <sub>-0.13</sub>	0
$\mu^{\pm}\mu^{\pm}$	0.9	1.1±0.4	1

#SUSY signal (per ch) ~ 0.2 – 3 events



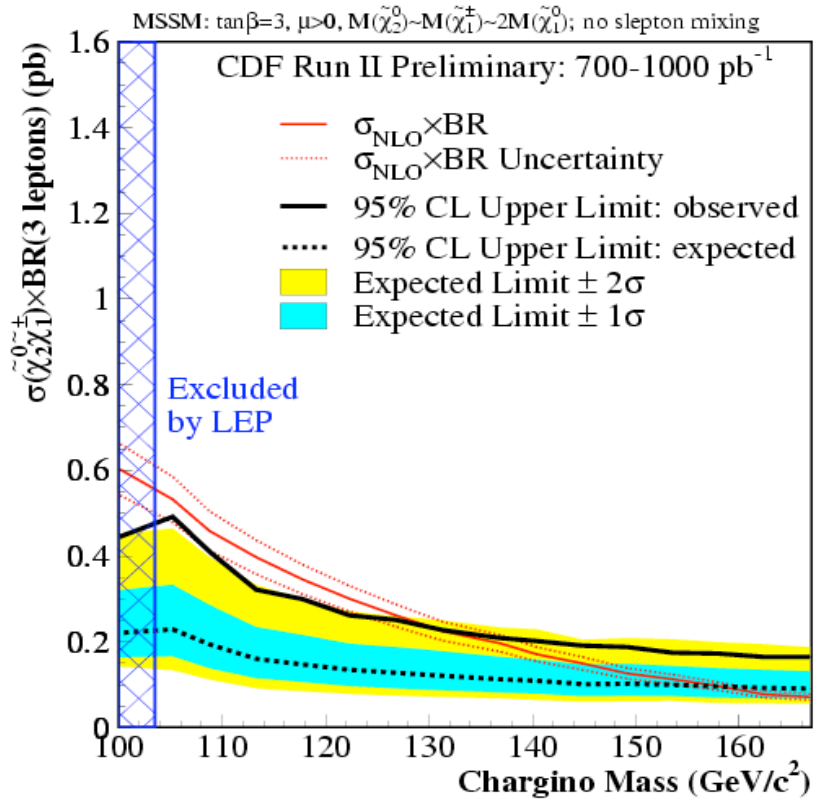




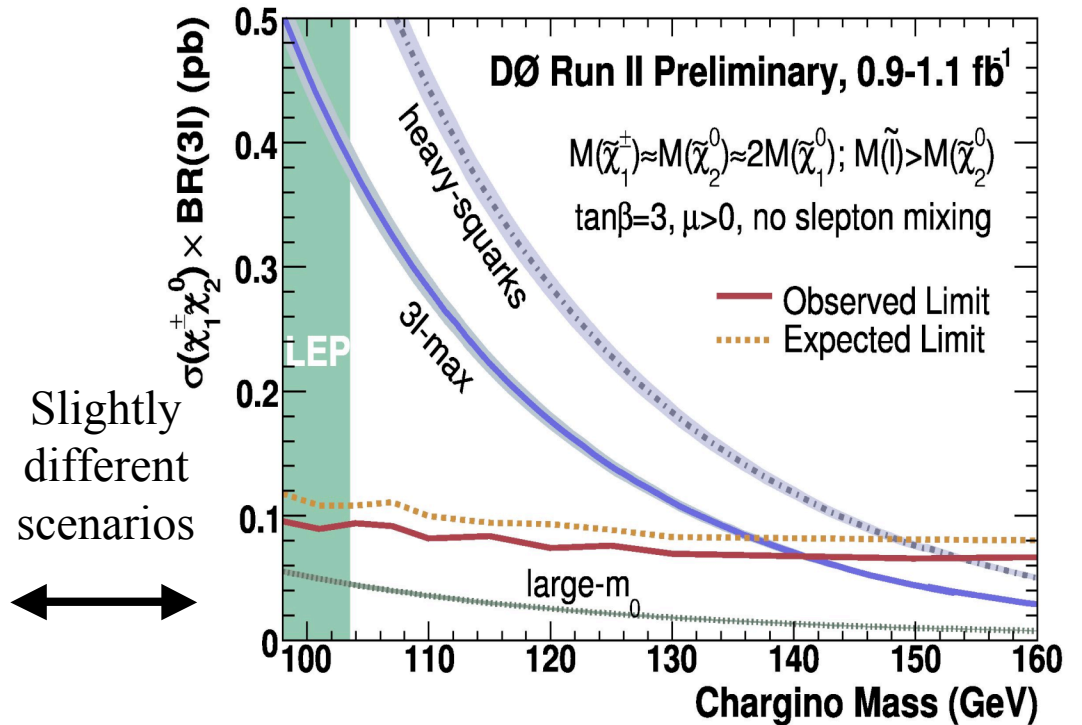
# Searches for Chargino/Neutralino in MET+Leptons



- Results of various channels are combined
- Present limits in mSUGRA like, low  $\tan\beta$ , no slepton mixing scenario



- Obs. limit :  $M_{\tilde{\chi}_1^\pm} < 130 \text{ GeV}/c^2$
- Exp. limit :  $M_{\tilde{\chi}_1^\pm} < 160 \text{ GeV}/c^2$



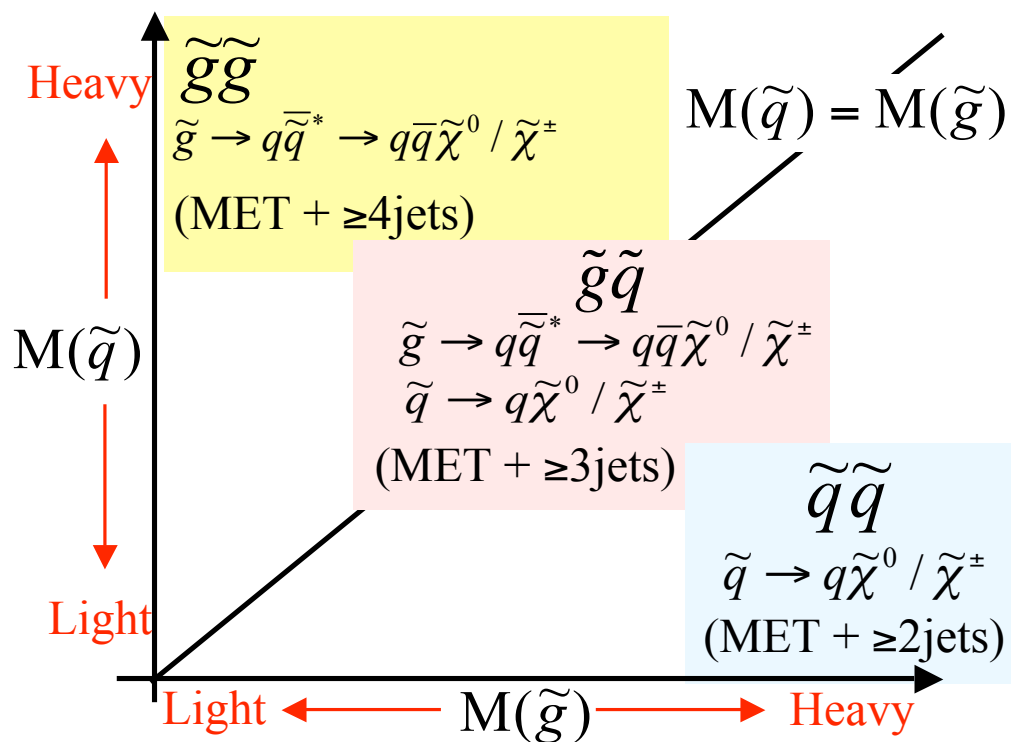
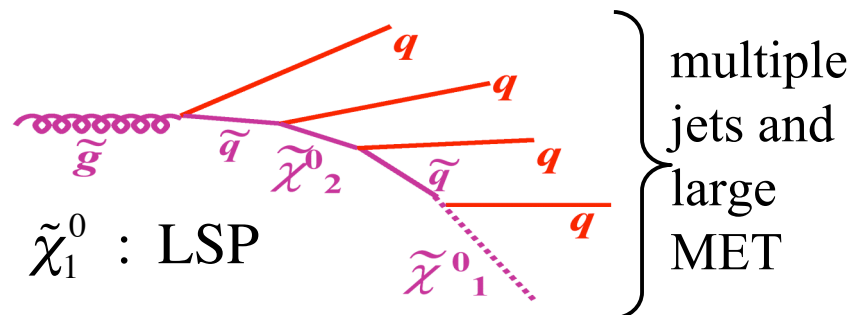
Slightly  
different  
scenarios  
↔

- 3l-max ( $M_{\tilde{l}} \geq M_{\tilde{\chi}_2^0}$ , lep. decay max. enhanced)
- Obs. limit :  $M_{\tilde{\chi}_1^\pm} < 141 \text{ GeV}/c^2$

• Exceed LEP's limit in these scenarios

# Searches for Squarks/Gluinos in MET+Jets

- $\tilde{q}, \tilde{g}$  can be pair produced at Tevatron
- Decays of  $\tilde{q}, \tilde{g}$  may produce multiple jets and large MET (Rp conservation)



- Main Background after clean-up
  - QCD multi-jet (fake large MET)
  - $Z(\rightarrow \nu\nu)$ +jets (irreducible)
  - $W(\rightarrow l\nu)$ +jets (missed lepton)
  - Diboson,  $t\bar{t}$

# Searches for Squarks/Gluinos in MET+Jets

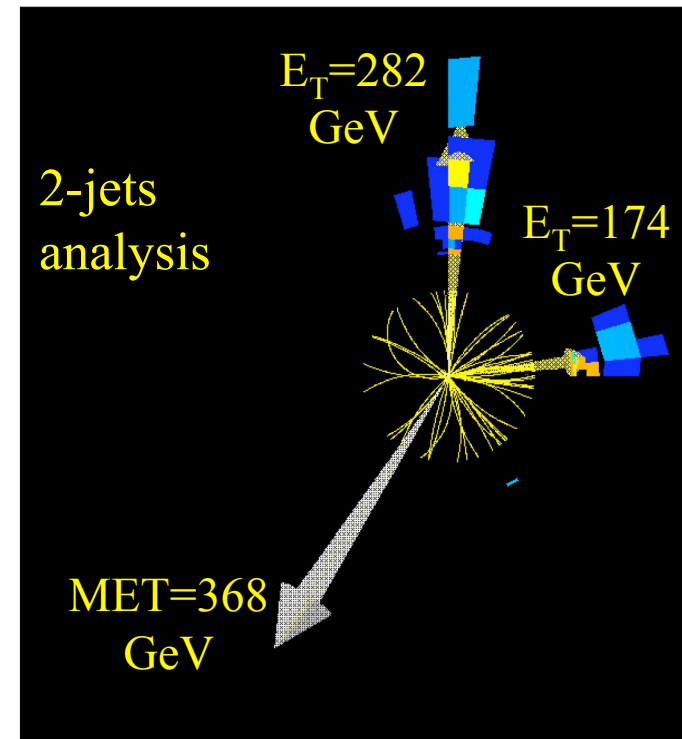
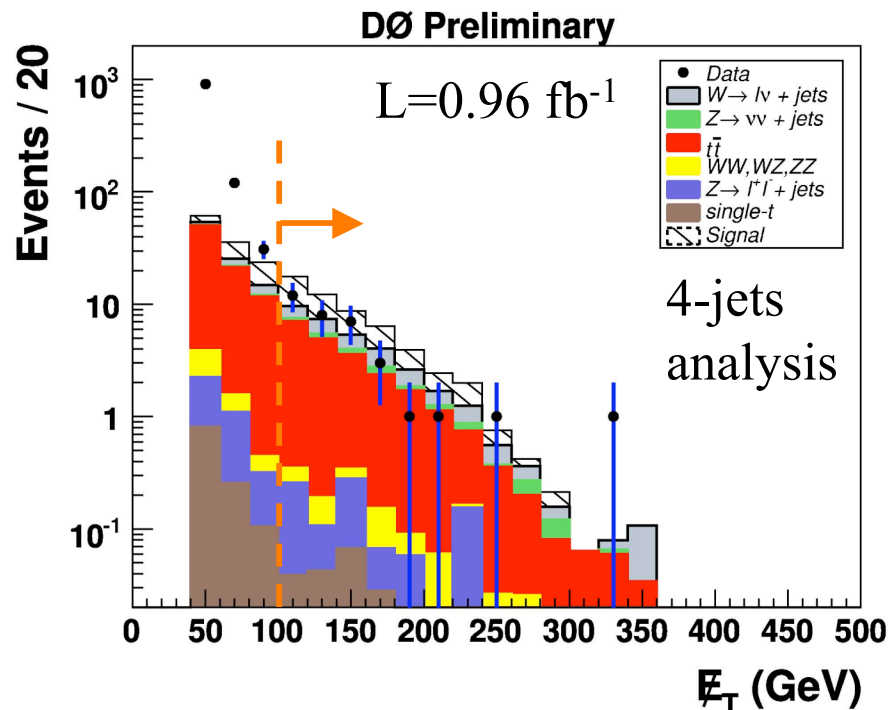


•DØ performs separate analyses for each final states ( $\geq 2, 3, 4$  jets+MET), to obtain best optimized signal to background separation

•Main selection cuts:

- Multi-jets + MET
- Separation of MET direction and jets
- Lepton veto
- Large  $H_T$  + large MET

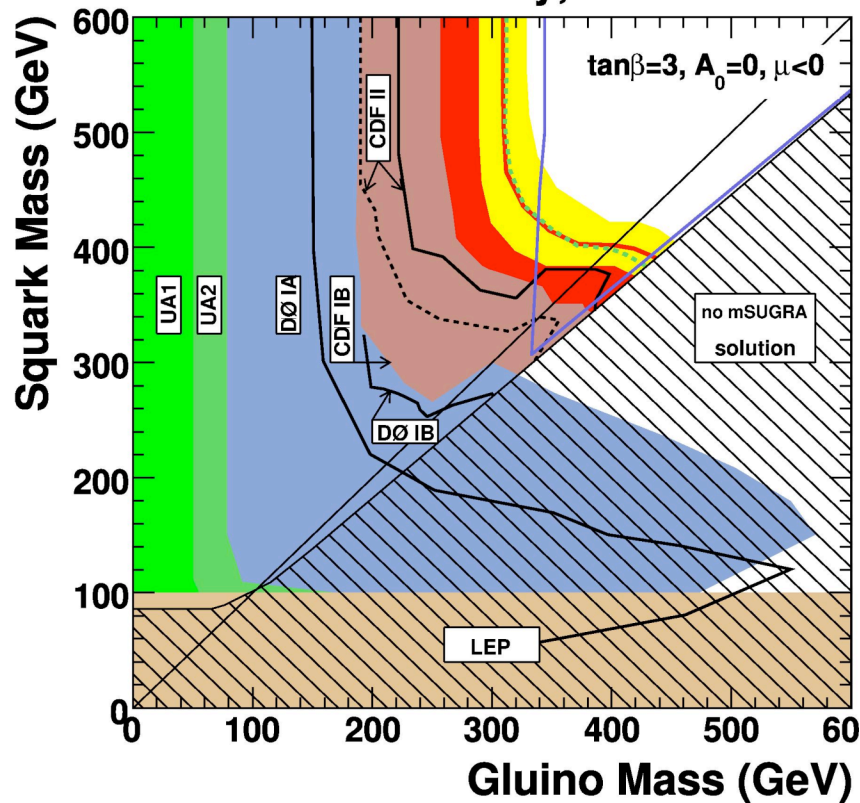
	# obs	# expected
2-jets	5	$7.5^{+1.7}_{-1.5}$
3-jets	6	$6.1^{+1.3}_{-1.2}$
4-jets	34	$33.4^{+5.6}_{-5.0}$



# Searches for Squarks/Gluinos in MET+Jets



DØ Preliminary, 0.96 fb<sup>-1</sup>

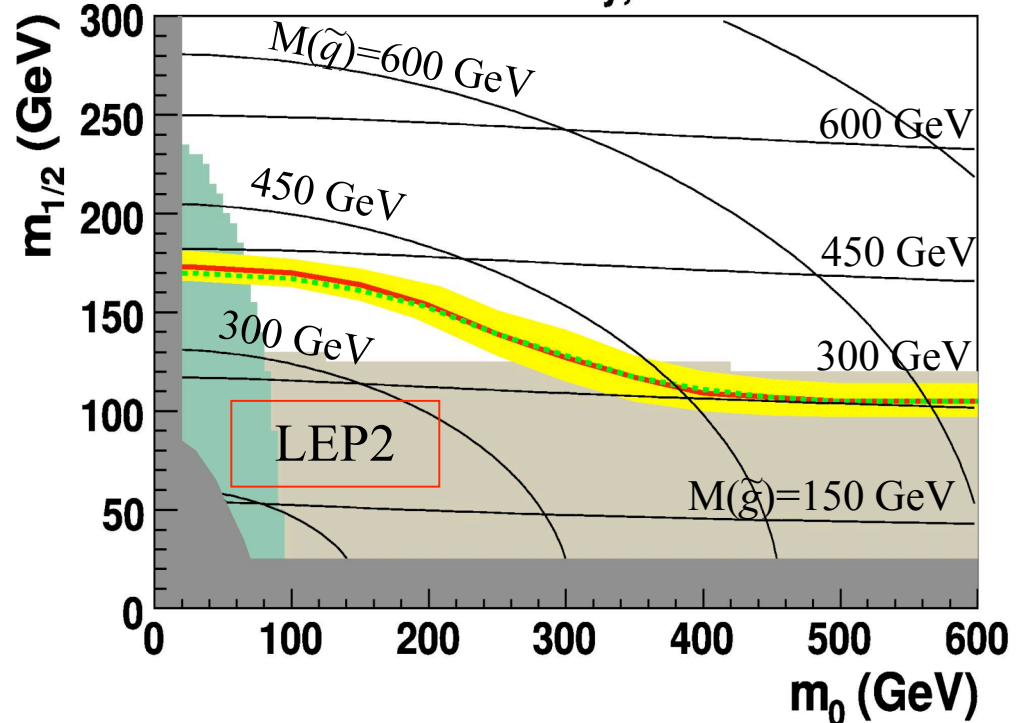


- Determine limits in mSUGRA framework
- Red curve : new 95% CL exclusion
- Yellow band : effect from theory cross section uncertainties

$$M(\tilde{g}) > 289 \text{ GeV}; M(\tilde{q}) > 375 \text{ GeV}$$

$$M(\tilde{g}) > 402 \text{ GeV (when } M(\tilde{g}) \sim M(\tilde{q}) \text{)}$$

DØ Preliminary, 0.96 fb<sup>-1</sup>



- This analysis also constrain the mSUGRA parameters ( $m_0$ : common scalar mass,  $m_{1/2}$ : common fermion mass)
- Extend limits beyond LEP
- CDF 1fb<sup>-1</sup> results coming soon



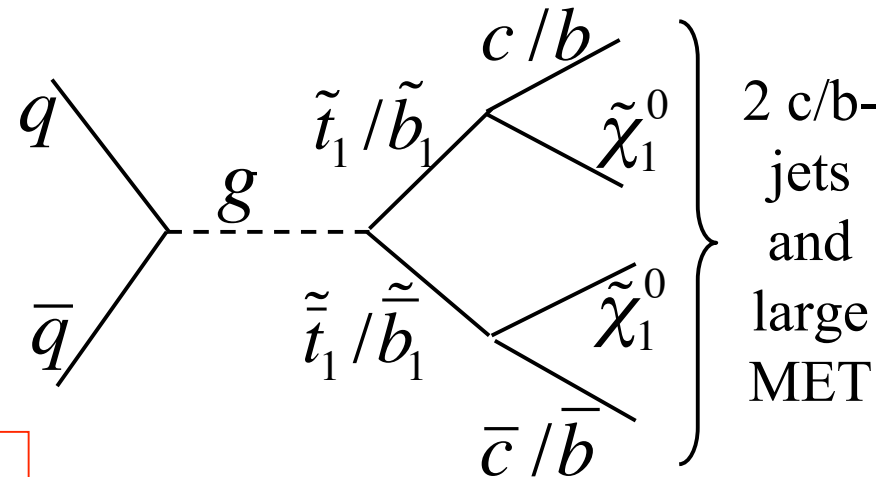
## Search for Third Generation Squarks



- Large mixing between the L- and R-handed weak eigenstates
  - Stop : due to large top quark mass
  - Sbottom : large mixing occurs at high  $\tan\beta$
- $\Rightarrow$  one of the stop and sbottom quarks can be light

### Search for Stop/Sbottom Quarks in MET+Jets

- CDF, DØ searched for stop/sbottom quark pair production
- Assume:  $\text{BR}(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = 100\%$   
 $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 100\%$



#### Main Selection:

- 2,3 jets, with  $\geq 1$  jet tagged as c/b-jet
- Large MET ( $> \sim 50$  GeV)
- Separation of MET direction and jets
- Lepton veto

#### • Main Background

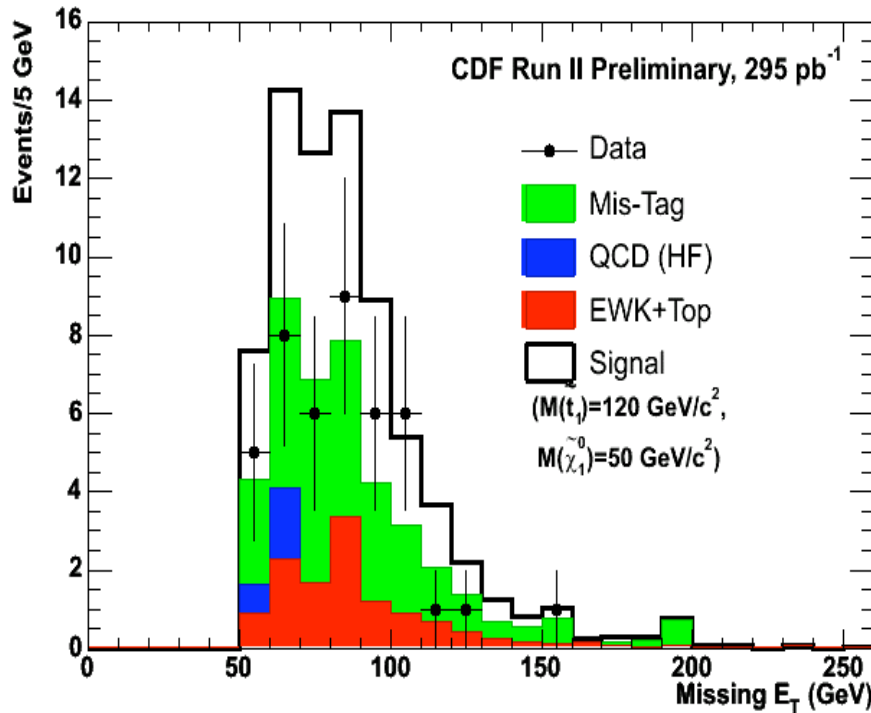
- $Z(\rightarrow \nu\nu) + \text{jets}$ ,  $W(\rightarrow l\nu) + \text{jets}$
- Di-boson,  $t\bar{t}$
- QCD multi-jet



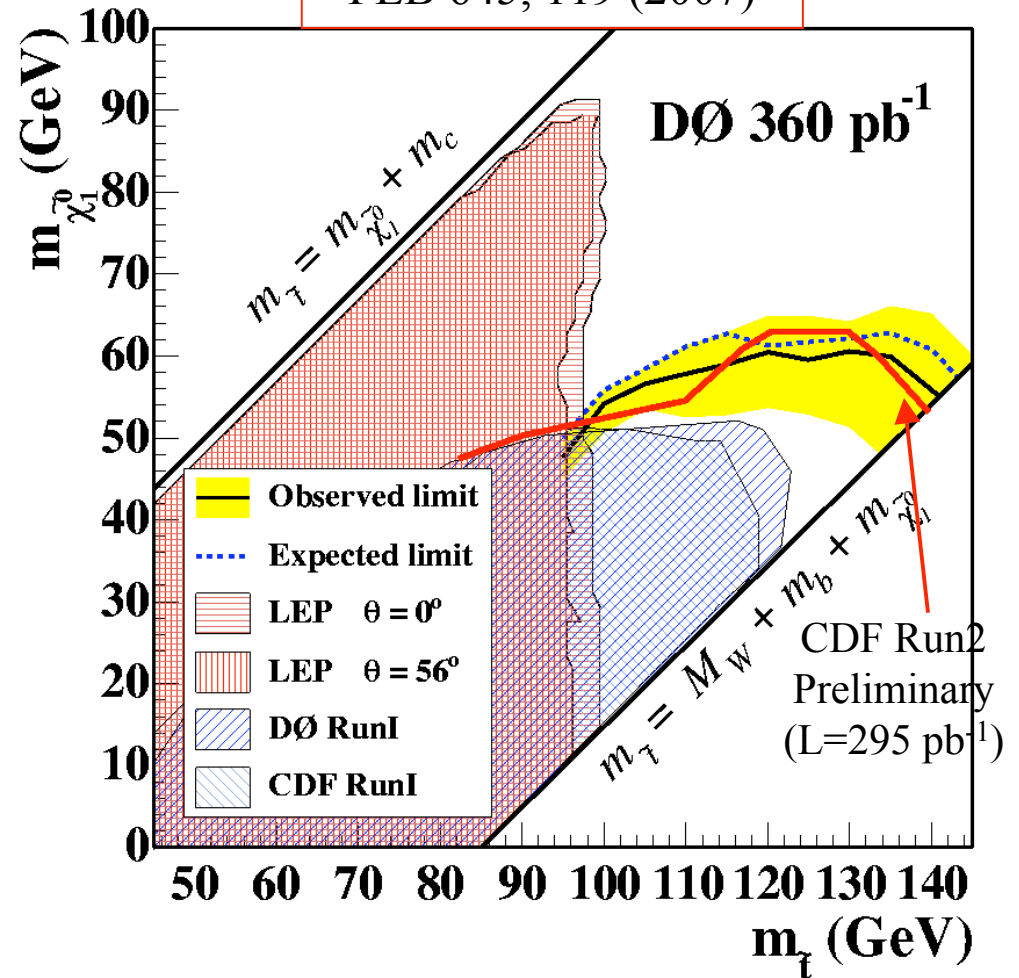
# Search for Stop Quark



PLB 645, 119 (2007)



Good agreement between Data and SM prediction (after all selection cuts)



Both CDF and DØ exclude  $M(\tilde{t}_1) < \sim 140$  GeV, for  $M(\tilde{\chi}_1^0)=55$  GeV at 95% CL

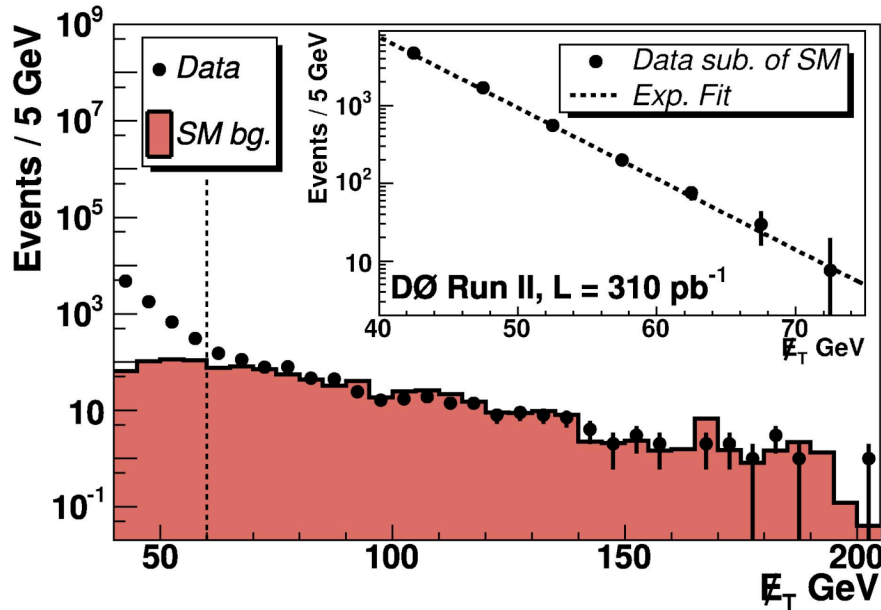




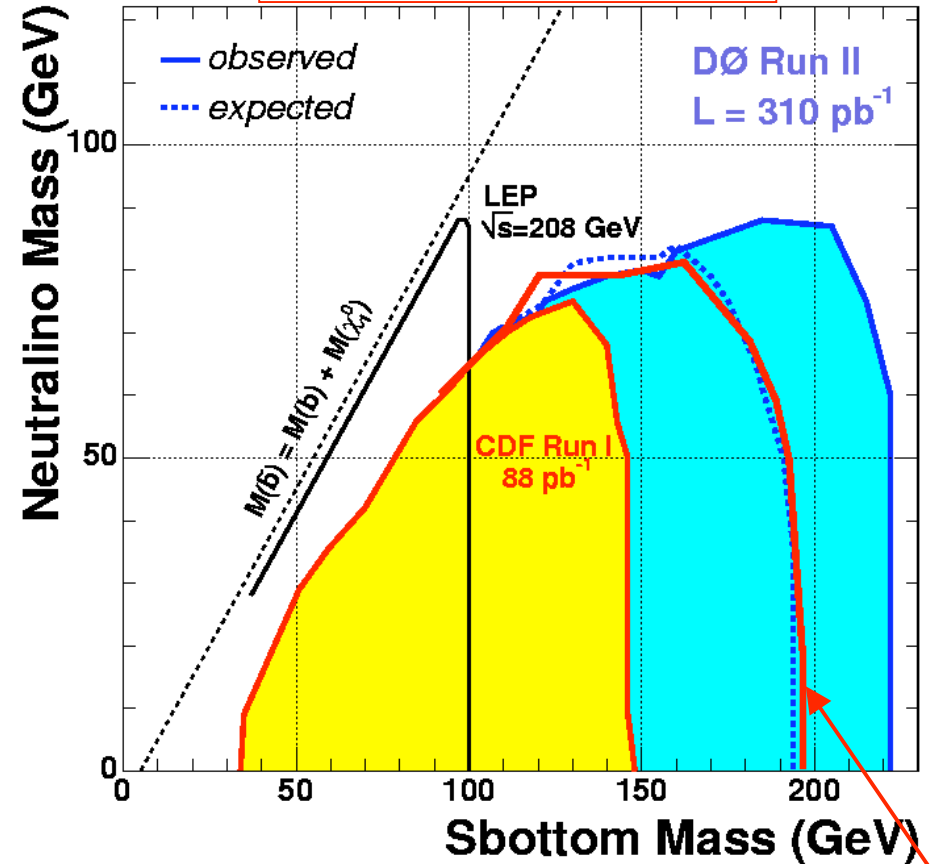
# Search for Sbottom Quark



PRL 97 171806 (2006)



- MET distr. after pre-selection cuts
- Data well described by expected SM contributions (low MET dominated by QCD, not simulated)
- After applying all cuts and b-tagging, found no excess in Data above SM prediction



Exclusion (@ 95% CL) :

DØ :  $M(\tilde{b}_1) < 222$  GeV

CDF :  $M(\tilde{b}_1) < 195$  GeV

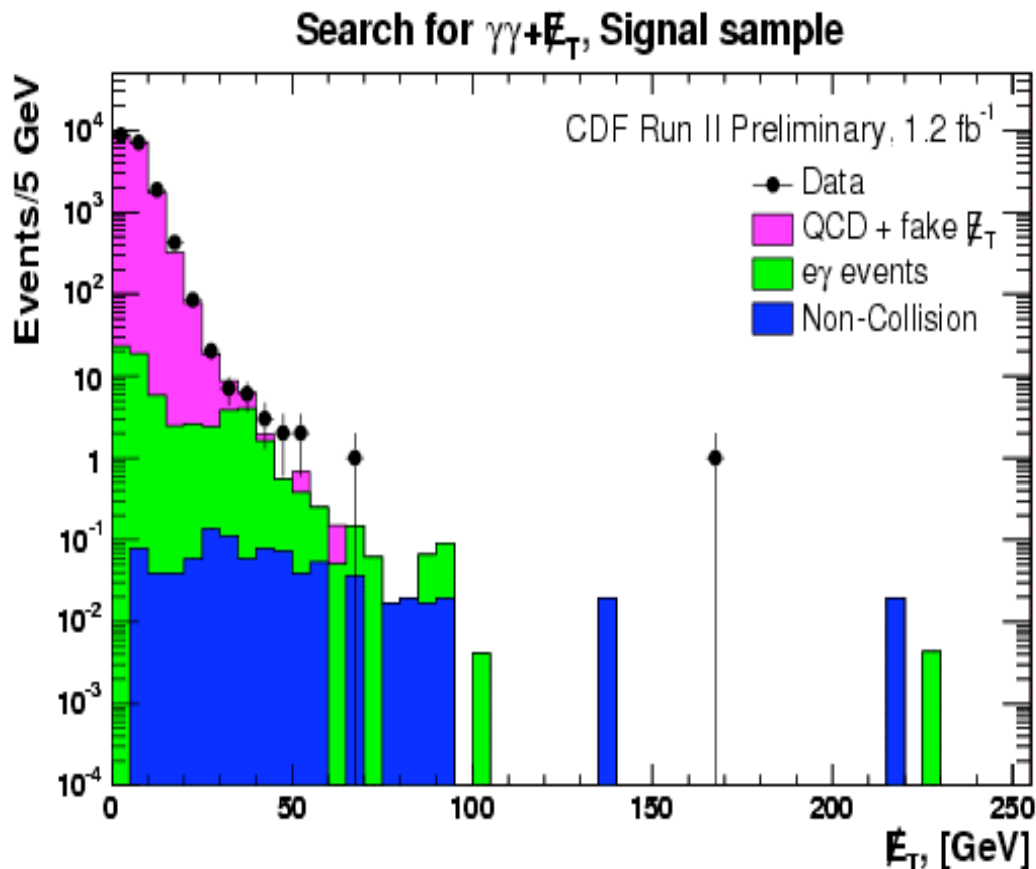
CDF Run2  
Preliminary  
(L=295 pb<sup>-1</sup>)



## Search for SUSY in MET+Di-Photon

- In GMSB, gravitino  $\tilde{G}$  is the LSP (escape undetected)
- If  $\tilde{\chi}_1^0$  is NLSP, then  $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$

$\Rightarrow$  Thus in SUSY production under GMSB, final state will consist of  $\gamma\gamma + \text{Missing Et} + X$



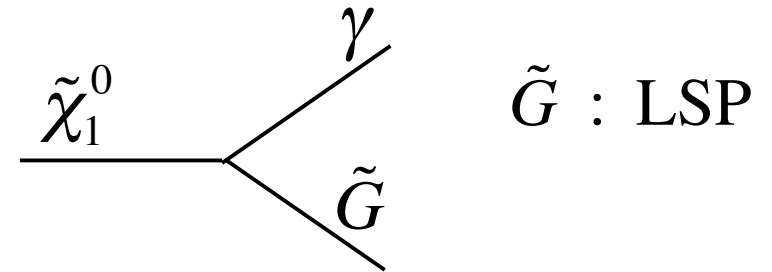
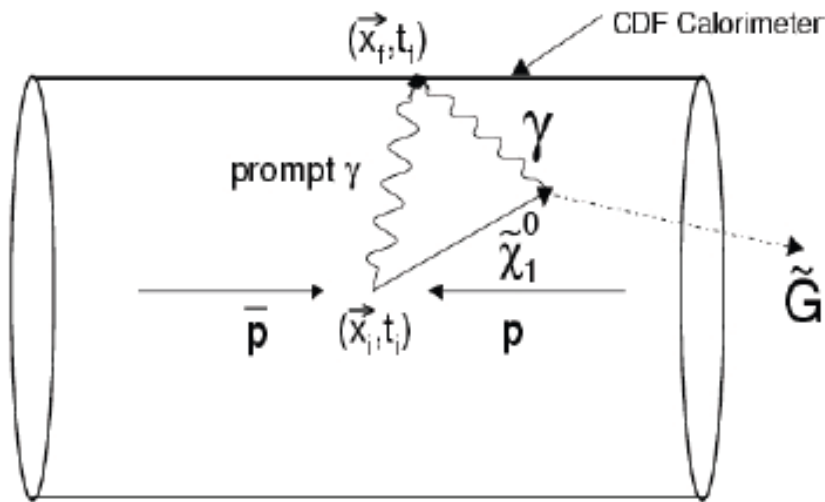
- CDF search for New Physics in  $\gamma\gamma + \text{Missing Et}$  signature
- Signature base search, not optimized for any particular model
- Require 2 central photons with  $E_T > 13$  GeV
- Observe no excess at high MET
- DØ previous search (760 pb<sup>-1</sup>) observe no excess, set limit  $M(\tilde{\chi}_1^\pm) > 220$  GeV





## Search for SUSY in Delayed Photon Signature

- CDF search for heavy long lived particle decaying (inside detector) into photon
- Focus on GMSB model where lifetime of  $\tilde{\chi}_1^0$  (NLSP) is free parameter



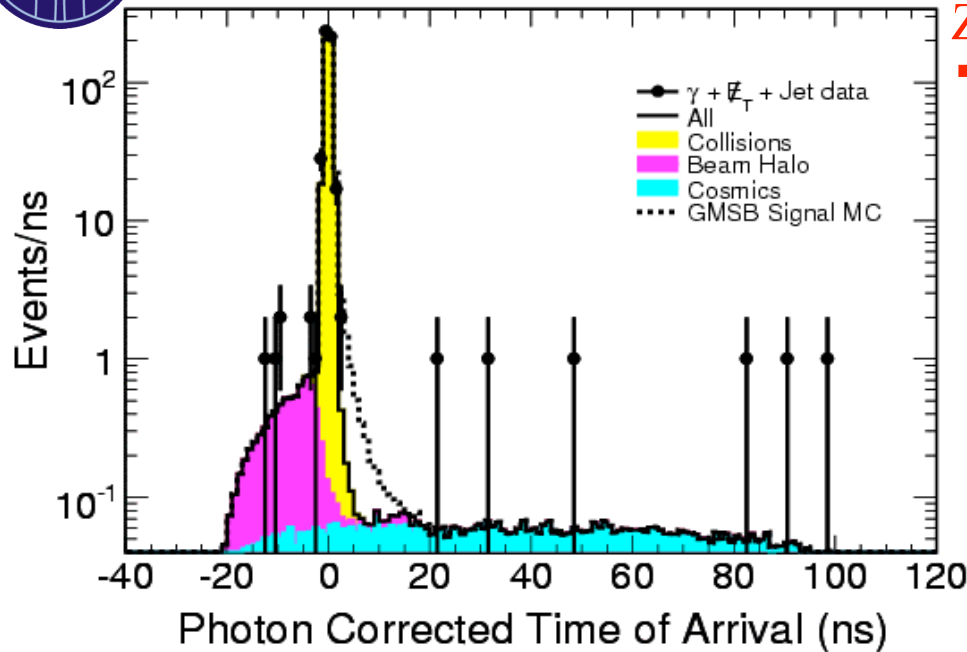
- $\tilde{\chi}_1^0$  is long lived and decays into  $\gamma$  and  $\tilde{G}$
- $\gamma$  from  $\tilde{\chi}_1^0$  decay will arrive at face of detector with time delayed relative to promptly produced  $\gamma$

- Select events with  $\gamma$ +MET+jet signature :
  - $E_t(\gamma) > 40 \text{ GeV}$
  - $E_t(\text{jet}) > 35 \text{ GeV}$
  - $\text{MET} > 40 \text{ GeV}$
- Arrival time of  $\gamma$  is measured by the timing system of the EM calorimeter

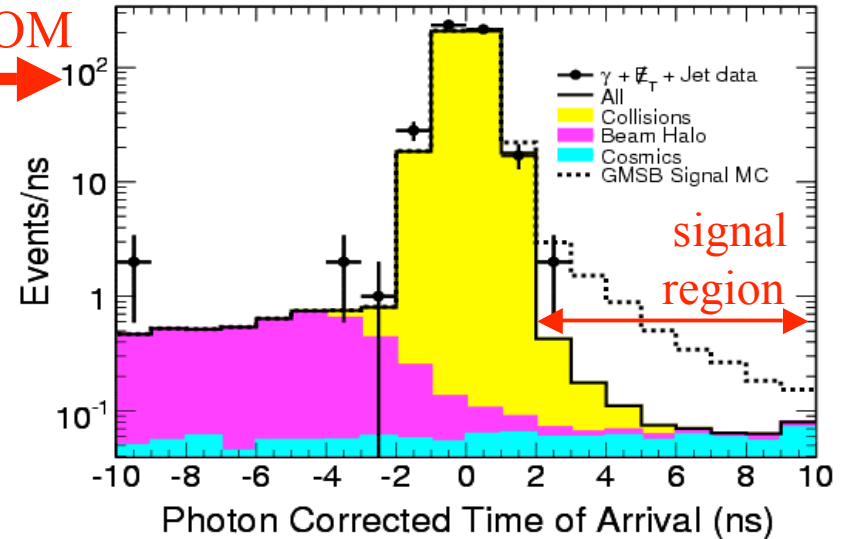


# Search for SUSY in Delayed Photon Signature

CDF Run II Preliminary, 570 pb<sup>-1</sup>

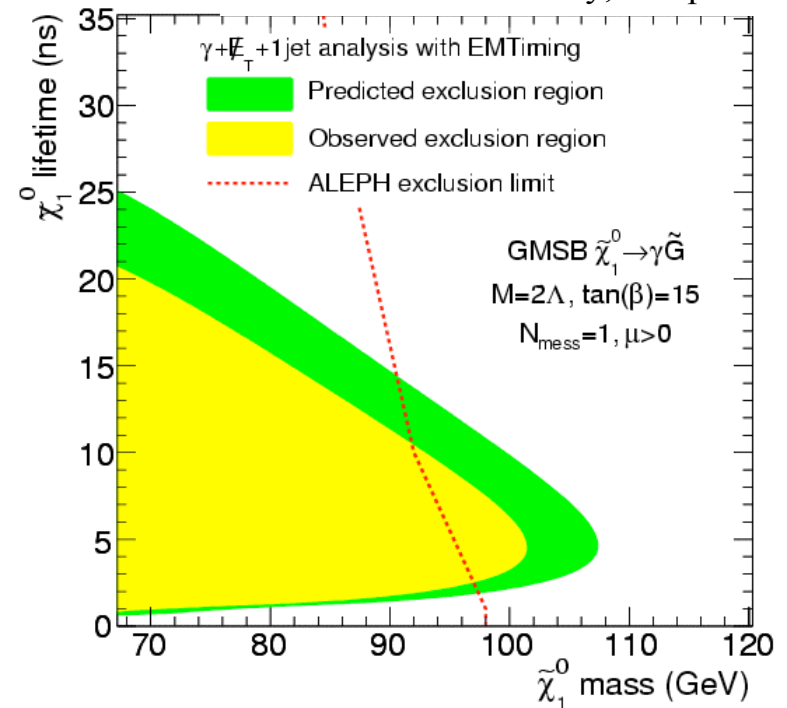


ZOOM



CDF Run II Preliminary, 570 pb<sup>-1</sup>

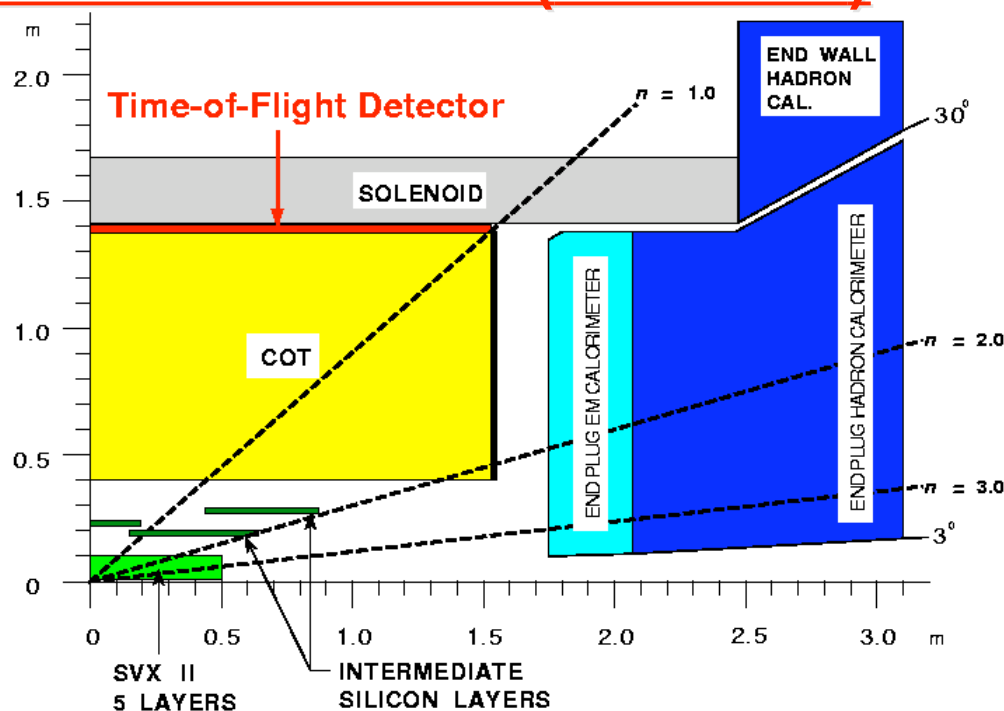
- $\gamma$  time corrected for TOF assuming coming from interaction point
- Signal window 2-10 ns
- Predict  $1.3 \pm 0.7$  BG events
- Observe 2 events
- Set exclusion in  $M(\tilde{\chi}_1^0)$  and  $\tilde{\chi}_1^0$  lifetime plane





# Search for CHArge Massive Particles (CHAMPs)

- CDF search for long lived particles :
  - Massive
  - Carry charge
  - Decay outside the detector
- These CHAMPs particles
  - Slow moving (long time of flight)
  - Very penetrating (like “slow muon”)
- Look for “muon” like particle penetrate through calorimeter to the muon chambers
- Use Time-of-Flight (TOF) detector to measure  $\beta$
- Use track momentum and  $\beta$  to calculate mass



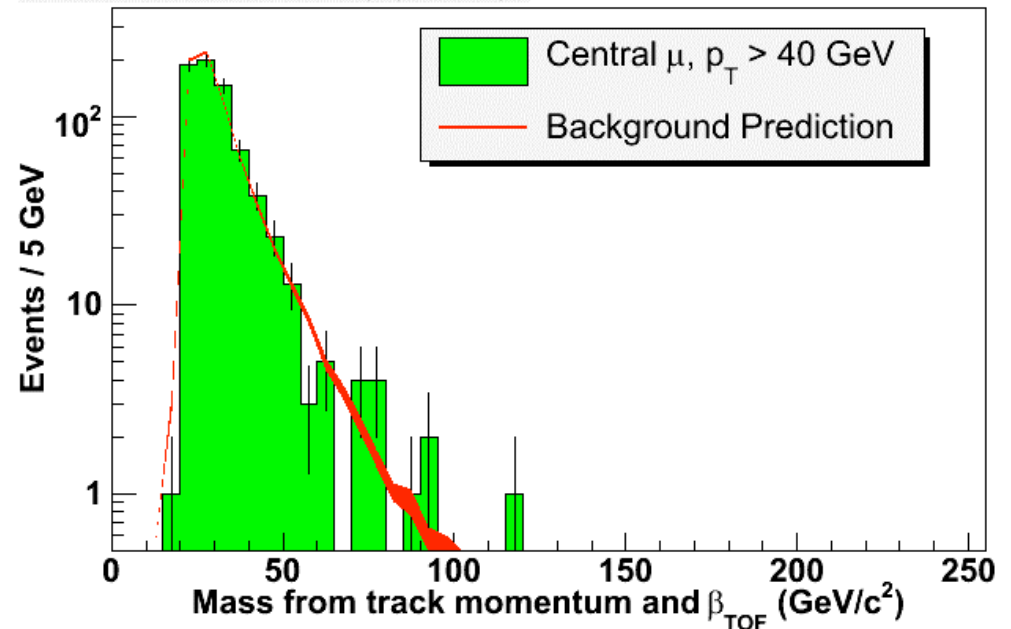
- Main background :
  - Cosmic
  - Instrumental effect :
    - Mis-measurement of interaction time and arrival time at TOF
    - Mis-measurement of momentum



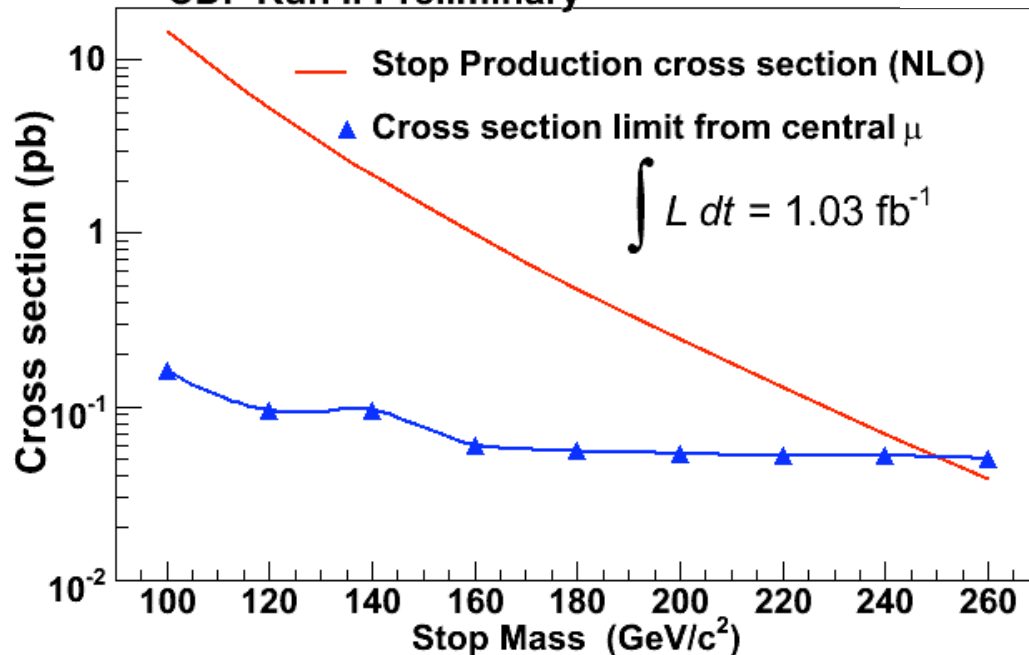
# Search for CHarge Massive Particles (CHAMPs)

- No excess in data at high mass
- $N_{\text{obs}}=1$ ,  $N_{\text{expect}}=1.5$   
( $\text{mass} > 100 \text{ GeV}$ )

CDF Run II Preliminary ( $1.0 \text{ fb}^{-1}$ )



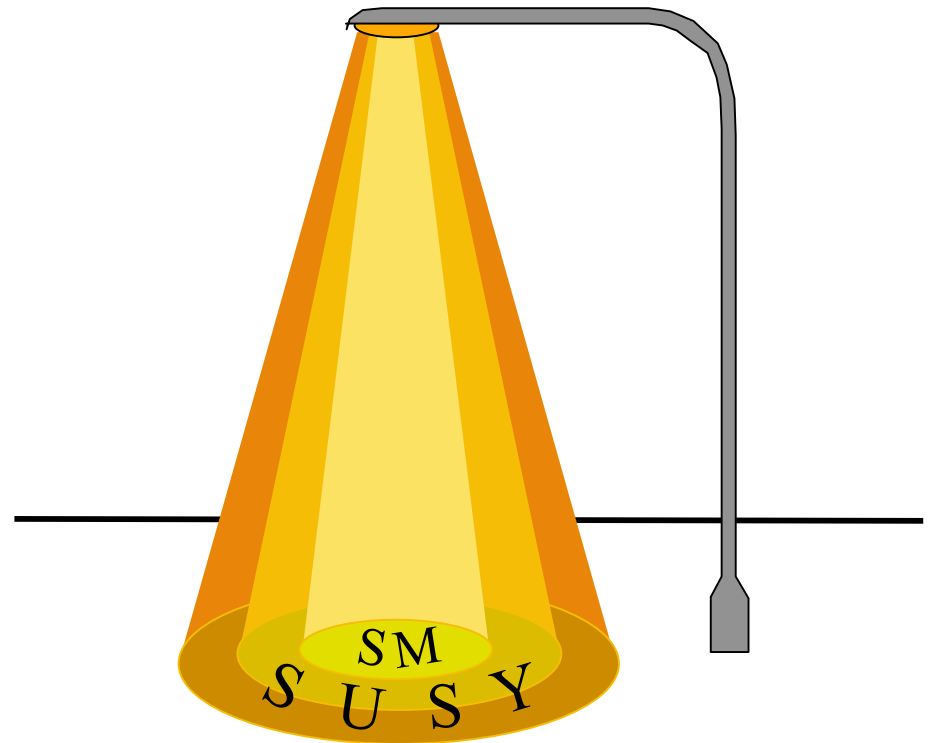
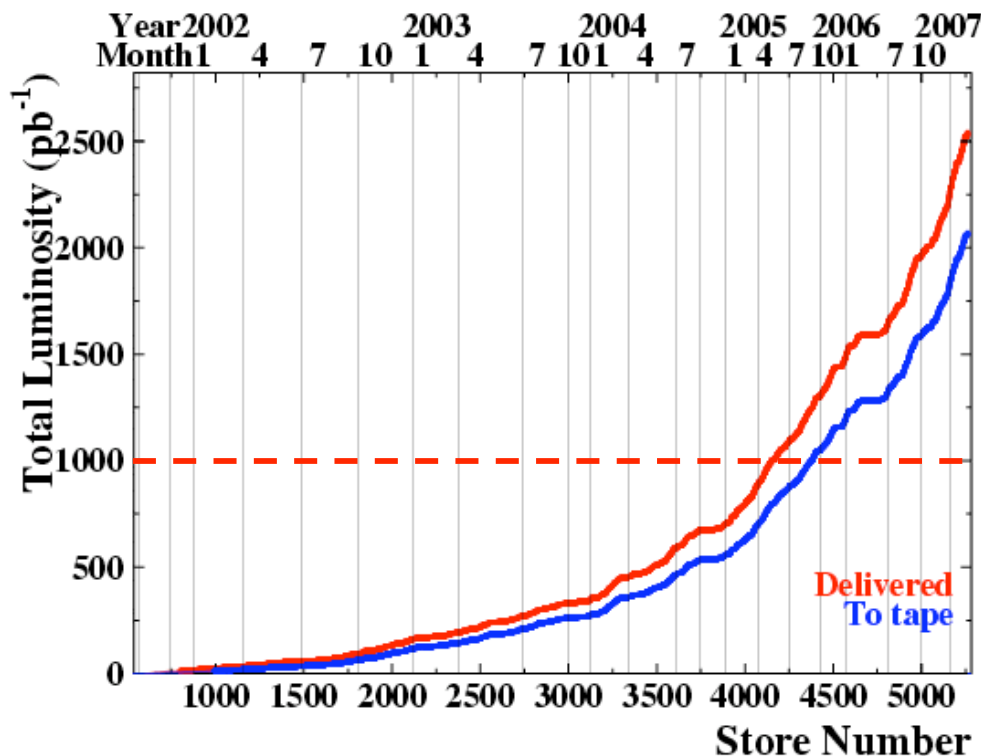
CDF Run II Preliminary



- Interpret results in stable stop quark model (R. Barbieri, L.J. Hall, and Y. Nomura, PRD 63, 105007 (2001) )
- Exclude stable stop quark  
 $M(\text{stop}) < 250 \text{ GeV}$  at 95% CL

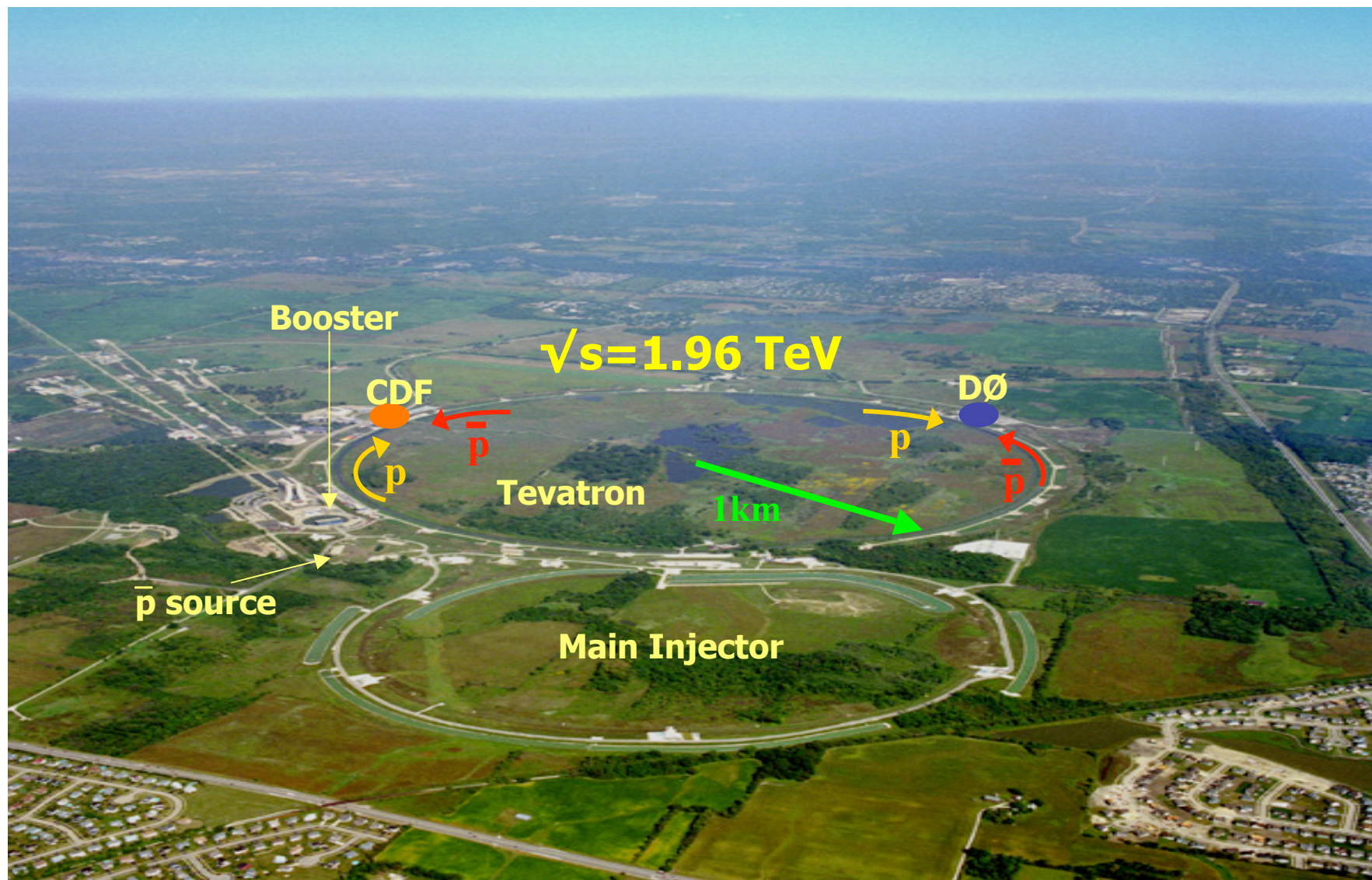
## Summary

- SUSY is a promising venue for New Physics
- CDF and DØ are mounting extensive program to search for it and other physics Beyond the Standard Model
- Just finished analysing 1 fb-1 data, and still have much more in the bag
- New Physics/SUSY may be just hiding in the shadow now ... can be observed with brighter “light” !!!





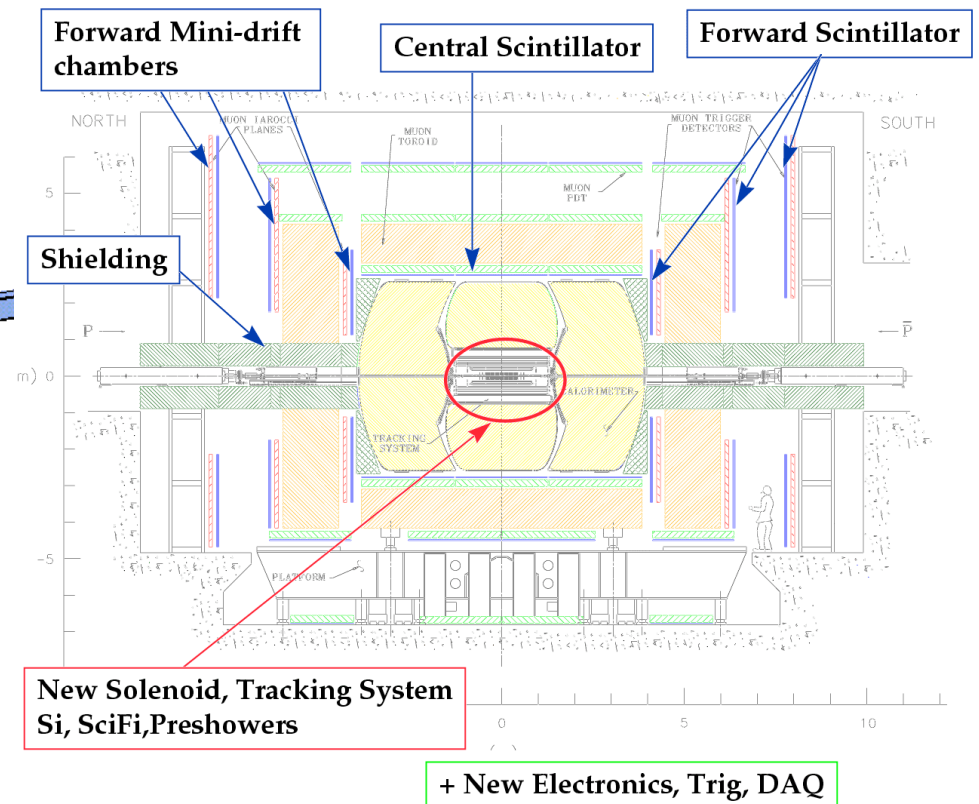
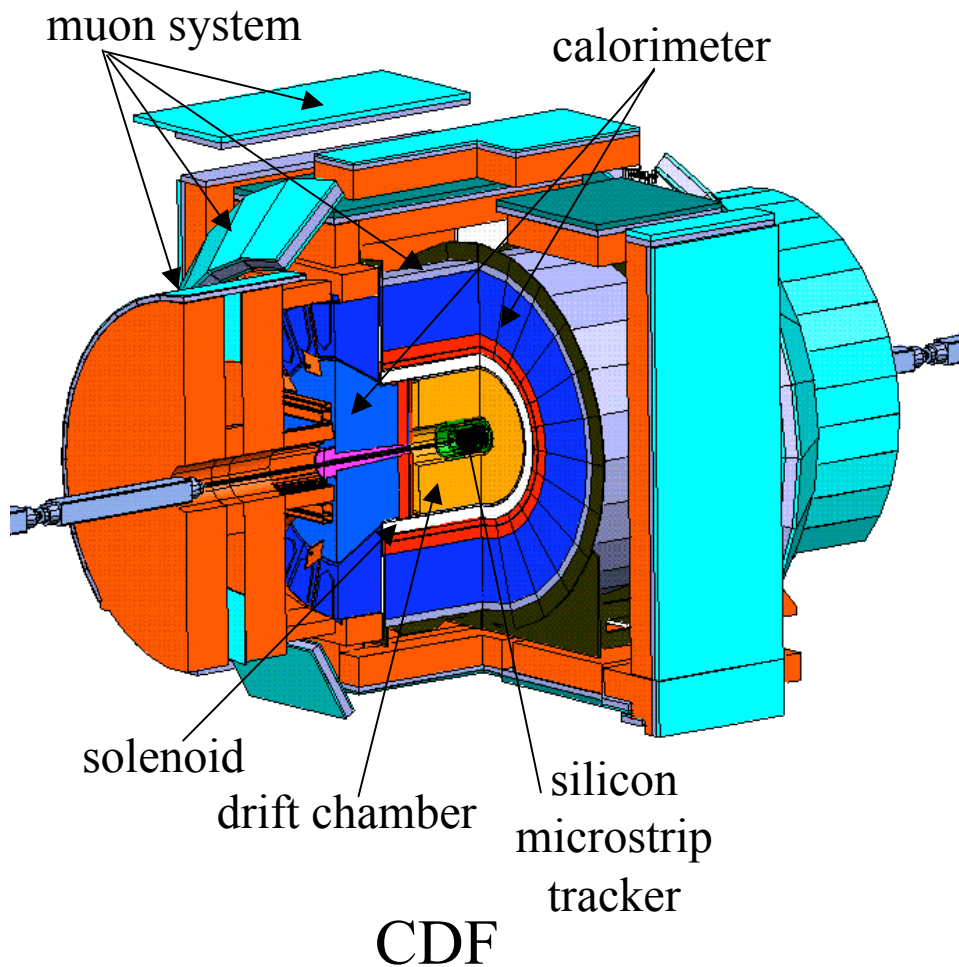
# Tevatron



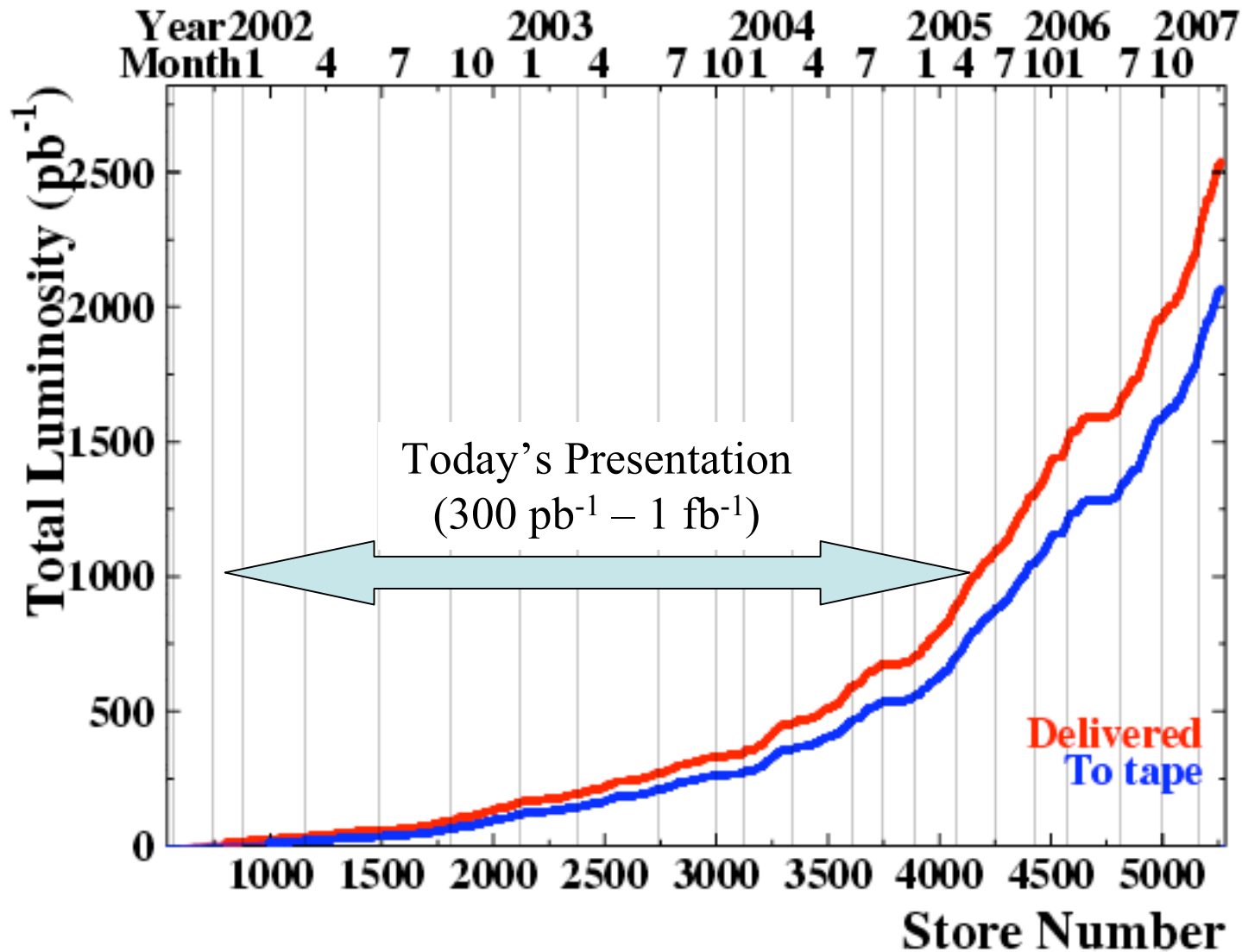
# The Tevatron Experiments

Multipurpose detectors :

- Electron, muon, tau identification
- Jet and missing energy measurement
- Heavy-flavor tagging through displaced vertices and soft leptons



## Tevatron Run2



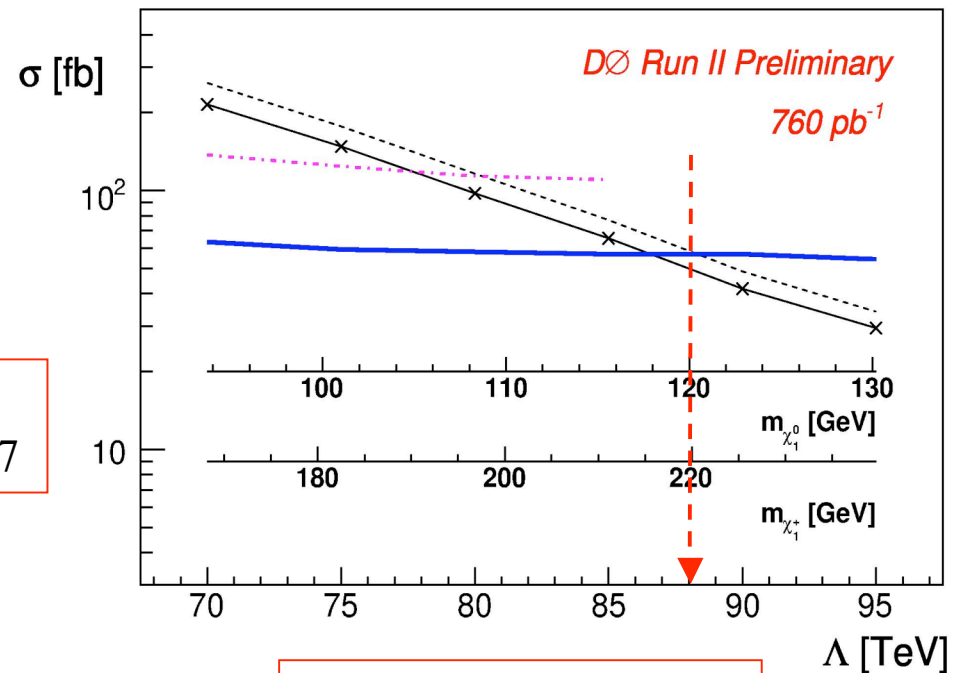
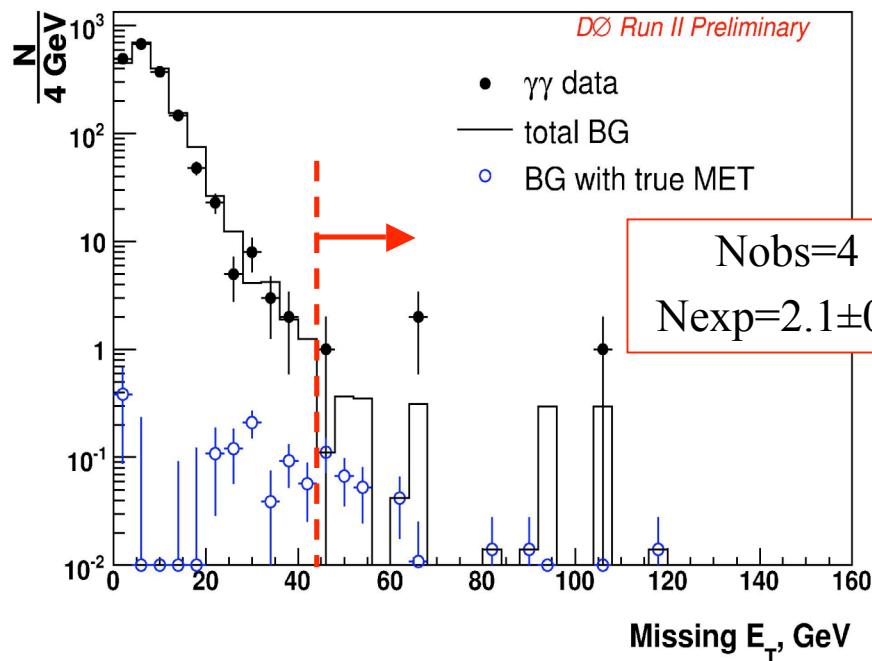
- Tevatron delivered total integrated lumi  $\sim 2.5 \text{ fb}^{-1}$
- CDF/DØ collected  $\sim 2 \text{ fb}^{-1}$  data



# Search for SUSY in MET+Di-Photon



- In GMSB, gravitino  $\tilde{G}$  is the LSP (escape undetected)
- If  $\tilde{\chi}_1^0$  is NLSP, then  $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$   
 $\Rightarrow$  Thus in SUSY production under GMSB, final state will consist of  $\gamma\gamma + \text{Missing Et} + X$
- DØ searched for GMSB SUSY in  $\gamma\gamma + \text{Missing Et}$  signature
  - 2 photons,  $E_t > 25 \text{ GeV}$
  - Missing  $E_t > 45 \text{ GeV}$



$$M(\tilde{\chi}_1^\pm) > 220 \text{ GeV}$$

# Non-Collision MET Background

Missing  $E_T$

